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REPORT No. R-667

MECHANISM OF COLLAPSE OF CONICAL HOLLOW CHARGE LINERS

FIRST REPORT PROJECT 3/324

by

[illegible]

ORDNANCE LABORATORY
FRANKFORD ARSENAL
PHILADELPHIA, PA.
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REPORT R-667

MECHANISM OF COLLAPSE OF CONICAL HOLLOW CHARGE LINERS

FIRST REPORT

PROJECT 3/324

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OBJECT

To obtain information on the mechanism of collapse of hollow charge liners by performing a metallurgical examination of the slugs recovered after firing selectively carburized cones for the M9A1 rifle grenade.

SUMMARY

This Arsenal was requested by Aberdeen Proving Ground to perform a metallurgical examination of the slugs recovered after firing selectively carburized cones for the M9A1 rifle grenade in order to obtain information on the nature of metal flow during deformation of the liners on firing and the temperatures developed in the slugs.

The results of the current investigation were in substantial agreement with Birkhoff's Jet Theory of liner collapse which postulates that the metallic flow in the liner can be approximated by assuming that the liner material behaves like a non-viscous liquid under the high rate of strain imposed by detonation. This theory had received substantial support from high speed radiographic studies conducted by Seely and Clark.

It appears that the flattened apex of the M9A1 conical lining is inverted by the pressure wave. Beginning at the apex, the cone then progressively collapses inward. As the metal meets along the axis, the material near the inner cone surface is apparently squeezed out along the symmetrical avenues of escape. The formation of a high speed slender jet moving ahead of a relatively low speed slug is explained in this manner.

The energy expended in deforming the liner material induces heating of the slug. Microstructural examination indicates that in the center, where deformation is very pronounced, the temperature exceeded the lower critical temperature for steel. There is no evidence of incipient fusion. It is not possible to assign a precise value for the maximum temperature, but it was probably in the range 1400°F to 2400°F. The maximum temperature at the surface of the slugs where the metal was deformed to a lesser degree is believed to have been in the neighborhood of 950°F. to 1200°F.

Comparison with observations made in the slug formed from the hollow charge liner of a 7.2" rocket indicates that the larger cones collapse in a manner similar to that of the M9A1 liners.

It is recommended that similar studies be made on liners of various design made with different materials.

AUTHORIZATION

1. APG (C) 472/12; SPOBA 400.112/12812-1
2. Memo for Record and Approval of Expenditures, 26 July 1944.

I. INTRODUCTION

Aberdeen Proving Ground has performed and sponsored an extensive amount of research work on the mechanism of collapse of hollow charge liners and on the perforation of armor by lined hollow charges.

Seely and Clark [1] have summarized the earlier information and theories on the functioning of hollow charge liners. The oldest theories of the cavity effect ignored the collapse of the liner and attributed the penetration of armor to a focusing of the shock waves by the shape of the cavity. A later theory of Kistiakowsky, MacDougall and Messerly recognized that metal particles are the agents causing penetration. This theory postulated that jets of gas break through the metallic liner, carrying fragments produced by rupture and erosion of the liner; an interaction of the jets was said to cause a strong forward wave which imparted a high velocity to the metallic particles. Another theory was that metallic particles are spalled off the inside of the liner and are focused by collision with each other at high velocity.

Seely and Clark [1,2] prepared high speed radiographs showing various stages in the deformation of hollow charge liners. These pictures suggested that the conical lining collapses with a normal velocity of 2500 to 3000 meters per sec. and that when the different sides collide along the axis, the metal is forced out along the symmetrical avenues of escape, thus forming a slender high speed jet ahead of a thick relatively low speed jet or "slug". There was no evidence that a spalling of the interior accounted for the formation of the jet.

Concurrently with the above radiographic studies, Birkhoff [3] formulated a jet theory of liner collapse based on a mathematical analysis of the deformation. In brief, Birkhoff assumed that the elastic and plastic resistance of the liner material could be neglected under the high rate of strain imposed by detonation and that the flow behavior could be approximated through calculations based on hydrodynamic equations for the flow of nonviscous liquids. The theory diverges sharply from the focussing, spalling and shock wave theories for hollow charge performance in that it postulates the formation of a jet of metallic matter by a squeezing of the core material as the walls collide along the axis.

Birkhoff's jet theory correlated well with the observations noted in the high speed radiographic studies. Not only did the qualitative description of the formation of the jet and slug fit in well with the observation of Seely and Clark, but in addition Birkhoff made calculations of the relative masses and velocities of the forward jet and the heavier slug which he believed to be in reasonable agreement with data obtained during the radiographic studies.

(1) References at end of report

Aberdeen desired to obtain further confirmatory information on the nature of metal flow during collapse of the liners and on the maximum temperature of the slug. This work is inhomogeneously distributed; there is an increase in the amount of deformation in going from the surface to the center of the slug. Accordingly, the center would be expected to reach a relatively high temperature, possibly above the melting point. The core then would be more plastic than the surface layers of the slug.

Aberdeen consulted Frankford Arsenal on the possibility of obtaining the desired information by performing a metallographic examination of the recovered slug.

At a conference of representatives of the two agencies, the use of tracer materials, either applied as a coating to the surface of the conical liners or selectively diffused into the surface of the cones, was discussed. It was reported that the use of a copper plating applied to the surface of the cone had not provided any additional information on the nature of metal flow during firing. It was agreed that a program for selective carburization should be performed. The displacement of the carbon-rich regions as a result of cone collapse should provide information on metal flow, while the structural changes in the steel should provide some information on the temperatures developed in the slugs.

Some earlier experiments on selective carburization of cones were not satisfactory because the "stop-off" used to inhibit carburization had failed to perform its intended function and the cones had been carburized over the entire surface.

The present report summarizes the procedure and results of a selective carburization program on M9A1 liners which has provided useful information on the mechanism of collapse of charge liners.

Concurrently with the program on M9A1 liners, Frankford Arsenal at the request of the Office, Chief of Ordnance, performed a metallurgical examination of a recovered slug which had been the liner of a 7.2" rocket. Since the results of the examination are pertinent to the present investigation, a copy of a letter report (4) to the Office, Chief of Ordnance, with minor editorial revision, is attached as Appendix A to this report.

II. PROCEDURE

A. Selective Carburization

Figure 1 shows the dimensions of the cone of the M9A1 rifle grenade and the assembly of the metallic components of the head of the grenade.

After development of a suitable carburizing cycle, six cones were to be selectively carburized in the zones listed below and shown in Figure 2:

Cone No.

1 - outside surface - center third of cone length
2 - inside surface - center third of cone length
3 - outside surface - region near mouth
4 - inside surface - region near mouth
5 - outside surface - region near apex of cone
6 - inside surface - region near apex of cone

Selective carburization was effected by using a copper stop-off to prevent carburization in regions removed from the selected zones. The following schedule was used after preliminary tests had indicated that the desired carburization could be obtained in this manner:

1. The cones were cleaned of all paint and grease.
2. A paraffin coating was applied to the surfaces in those regions which were ultimately to be carburized.
3. A copper electroplate, approximately 0.0015" thick was applied to the cones; the wax coated areas remained unplated.
4. The cones were box carburized at 1700°F for 1 1/2 hours, removed from the box, and cooled in still air.

Photomicrographs showing the structure, as observed on a pilot sample, are presented in Figure 3. It may be noted in Figure 3a at 100X that carbon had diffused from the unplated surface to approximately the center of the wall and that the copper electroplate on the opposite surface had completely inhibited carburization. Figure 3b at 1000X shows that the structure in the carburized zone adjacent to the surface consists of hypo-eutectoid ferrite and pearlite.

B. Firing Hollow Charges and Recovery of Slugs

The six selectively carburized cones were forwarded to Aberdeen for firing. The following is the description of the firing of the charges and recovery of the slugs as supplied by Aberdeen:

"The steel liners, with portions of their surfaces carburized, were assembled as components of the M9A1 Rifle Grenade. The grenades were fired statically while suspended, axis vertical, at a height of 30 inches above the top of an oil drum. The drum was filled with water in which was immersed a wire basket containing rock wool. The basket was about 18 inches high and occupied the bottom half of the drum. The drum was embedded into the ground, top level with the ground surface.

"After firing a grenade, the basket was lifted out and the rock wool was searched until the slug was recovered. The penetration of the slugs into the rock wool was about 5 to 10 inches. Thus, the slugs traversed about 30 inches of air space, 18 inches of water, and 5 to 10 inches of rock wool immersed in water. The temperature of the recovery medium was approximately 80°F."

III. EXAMINATION OF RECOVERED SLUGS

A. General Features

Figure 4 shows the external appearance of the slugs and fragments as recovered.

B. Macrostructure

The recovered slugs were sectioned longitudinally and deep-etched with an acidic copper reagent (40 ml. HCl, 30 ml. H_2O, 25 ml. C_2H_5OH, 5 g. $CuCl_2$). Figure 5 shows the macrostructure developed by this etching procedure at approximately two times natural size.

Carburization appears to have been localized to the desired areas except in pieces Nos. 1 and 5 where there was apparently some breakdown of the copper shielding coat on the inner surface of the cone. The undesirable carburization can be distinguished readily from the zones of intentional carburization and can be disregarded in interpretation. The following characteristics of the recovered slugs were noted by macroscopic examination of the recovered pieces:

1. Except for the region near the apex, carburized zones near the outer surface did not shift longitudinally to any considerable extent.

2. Carburized regions on the inner surface show evidence of a shift forward away from the apex of the cone. There is evidence that material in the center of the slug is displaced considerably from its original position.

3. There was a zone in the center of the slugs which etched at a different rate than the balance of the slug. This is shown to best advantage in Slugs Nos. 3 and 4. Microscopic examination, to be discussed subsequently, indicated that this zone had been heated to a temperature over the critical range.

4. Invariably an inverted V structure was developed near the apex. This structure was noted in all six cones, but is shown particularly well in slug No. 4.

5. All of the slugs broke at a distance 1/2" to 3/4" from the apex and at a distance approximately 2/3 of the length from the apex toward the mouth.

C. Microstructure

In all of the slugs there was a progressive change in structure from the center to the surface. Where the central areas had been carburized, the structure consisted largely of undistorted pearlite differing from the original pearlite and apparently formed as a result of transformations occurring during firing and recovery; this is shown in Figure 6a. There was no evidence of fusion of the metal. Where the steel had not been carburized, the structure consisted of recrystallized ferrite with some pearlite.

The regions near the surface contained distorted pearlite and distorted ferrite with some evidence of recrystallization of ferrite; the pearlite is more "granular" than it was in the unfired cone. The structure of a carburized zone near the surface is shown in Figure 6c. The structure of a transition zone between the center and surface is shown in Figure 6b.

IV. DISCUSSION OF RESULTS

It is believed that the mechanism of collapse described below and illustrated in Figure 7 is compatible with the observations noted above. The proposed mechanism is not original with this author; its principal features were suggested by the work of Birkhoff [3] and Seely and Clark [1,2]. A later section will indicate some characteristics of cone deformation which were not reported previously. It appears that the rounded apex of the cone is first inverted by the pressure wave. Beginning at the apex, the cone walls progressively collapse inward. An inverted V is formed by compression of the apex metal. As the outer dimensions diminish, ironing or thickening of the wall takes place. As the metal flows toward the center and meets, a forward stream or jet is formed along the symmetrical avenue of escape. Although the jets formed during detonation were not examined, the fact that the jets were formed by a squeezing of the material which was originally on the inner surface of the cone is strongly suggested by the manner in which the metal in the central areas was displaced forward away from the apex of the cone.

It is possible to account for the fact that all slugs broke at a distance approximately two thirds of the length from the apex on the basis that the rim of the cone offers too much resistance to permit the continuation of progressive deformation, and that rupture occurs with the rim being fragmented and scattered.

There is no really satisfactory explanation for the fact that all cones also broke near the apex. Macrographic examination indicates that there was no gross change in the mechanism of deformation at this level.

The microstructural changes developed on firing can be attributed to the energy expended during the very rapid deformation. As Birkhoff [3] indicated, there is greater deformation in the center than at the surface, and it is to be anticipated that the center of the slug should be heated to a higher temperature than the surface.

It is difficult to assign a value for the maximum temperature of the slug since the peak temperature was maintained for a very brief period. The rapid expenditure of energy caused an exceedingly rapid heating of the central areas, while the hot areas were probably cooled immediately by the surrounding colder metal. Even when a piece of steel is maintained at an elevated temperature for a considerable period of time and equilibrium is established by diffusion, it is difficult to make any precise statement with respect to the maximum temperature. Under nonequilibrium conditions, evaluation of temperature is at best an estimation.

Metallographic examination, Figure 6, indicates that fine pearlite has been formed in the center of the slug as a result of transformations occurring in the steel. This indicates that the pearlite originally present, Figure 3, must have been dissolved by heating to a temperature in excess of the lower critical (A_1 = 1350°F approximately). There is no evidence of a "burned" structure which would result from heating above the temperature at which incipient fusion is noted. The peak temperature thus is believed to have been somewhere in the range 1400°F to 2400°F.

Examination of the structure near the surface, Figure 6c, indicates that partial recrystallization of the ferrite has occurred; the carbides in the pearlitic areas have been agglomerated considerably, as compared to the original structure, but do not appear to have been dissolved. It is estimated that the maximum temperature near the surface was on the order of 950°F. to 1150°F.

In the intermediate zone, Figure 6b, the ferrite is completely recrystallized while the pearlitic areas have been distorted by deformation; the carbides in the pearlite have been agglomerated considerably but do not appear to have been dissolved. The temperature in this region apparently did not exceed the lower critical temperature (1350°F.).

The presence of pearlite in the central zone is somewhat difficult to explain since water quenching during recovery should be expected to produce hard martensite as a product of transformation of austenite formed on heating over the critical range. Martensite was actually noted in some preliminary tests. It appears that the slugs in the present program became buried in the rock wool at the bottom of the recovery tank; contact with the rock wool apparently prevented free contact with water and promoted the development of an insulating steam jacket. It thus appears probable that the slugs were cooled rapidly from the peak temperature to an intermediate temperature from which they cooled slowly to room temperature.

V. CORRELATION WITH HIGH SPEED X-RAY RADIOGRAPHIC AND BIRKHOFF'S JET THEORY

The results of the macrographic and micrographic studies are in excellent agreement with the information gained from high speed x-ray radiographic studies and provides additional confirmation for Birkhoff's Jet Theory. Birkhoff's comments to this effect, made after reading a letter report outlining the results of the current investigation, are attached to this report as Appendix B.

The inversion of the apex in an early stage of deformation, which is indicated by the inverted V structure, had not been noted previously. Birkhoff states that it is reasonable to anticipate such behavior, particularly in cones rounded at the apex; the M9A1 liners used in this investigation were rounded or flattened at the apex as shown in Figure 1.

VI. CORRELATION WITH INFORMATION AVAILABLE ON OTHER HOLLOW CHARGE LINERS

Comparison of the results of an examination of a recovered slug formed from the hollow charge cone of a 7.2" rocket, reported in Appendix A, with the M9A1 slugs, indicates many features of similarity. The mechanism of metal flow appears to have been similar; differential heating due to the energy of deformation is noted in both instances. Even the cracking of the slug near the apex region of the cone is similar.

VII. CONCLUSIONS

1. A metallurgical examination of the slugs formed by firing selectively carburized M9A1 conical hollow charge liners has provided additional confirmation of Birkhoff's Jet Theory of liner collapse as applied to such conical liners. This theory had already received substantial support from high speed radiographic studies conducted by Seely and Clark. It appears the apex of the cone is first inverted by the pressure wave generated by detonation of the

powder charge. The cone wall then progressively collapses inward beginning at the apex. As the metal flows toward the axis of the cone and meets, a forward stream or jet is formed along the symmetrical avenue of escape. A breaking of the slugs at a point approximately two thirds of the length from the apex of this cone has been explained on the basis that the rim of the cone offers too much resistance to permit continuation of the progressive collapse and rupture of the cone occurs. Another break noted in all six slugs at a point 1/2" to 3/4" from the apex has not been explained.

2. The inversion of the apex mentioned above had not been noted previously. It has been indicated, however, that this inversion can be predicted by mathematical studies, particularly in cones like those employed in the M9A1 grenade which are flattened slightly at the apex.

3. The slug upon recovery shows a progressive change in microstructure from the center to the surface due to the fact that the slug was heated by the energy expended in deforming the slug. The central zone of the slug in which deformation was the greatest was heated above the lower critical temperature by the energy expended during collapse. It is difficult to assign a precise value for the maximum temperature because the slug presumably remained at the maximum temperature only a brief time during which equilibrium was not attained. There is no evidence of incipient fusion, and it is believed, therefore, that the maximum temperature of the slug was from 1400°F. to 2400°F. The surface of the slug, where deformation was less pronounced, had apparently been heated to a temperature between 950°F. and 1200°F.

4. Comparison with an examination of a slug formed from the hollow charge liner from a 7.2" rocket indicates that the larger cones collapse in a similar manner.

VIII. RECOMMENDATIONS

It is recommended that ballistic tests on shaped charges with liners of various designs and materials be supplemented with metallurgical studies similar to those reported herein as a means of obtaining additional detail information on the mechanism of liner deformation.

REFERENCES

1. L. B. Seely and J. C. Clark - "High Speed Radiographic Studies of Controlled Fragmentation. I. The Collapse of Steel Cavity Charge Liners", Ballistics Res. Lab., Aberdeen Proving Ground, Report No. 368, June, 1943.

2. J. C. Clark and L. B. Seely - "High Speed Radiographic Studies of Controlled Fragmentation. II. Motion of Explosion Gases in Lined and Unlined Cavity Charges", Ballistics Research Laboratory, Aberdeen Proving Ground, Report No. 392, July, 1943.

3. G. Birkhoff - "Mathematical Jet Theory of Lined Hollow Charges", Ballistics Research Laboratory, Aberdeen Proving Ground, Report No. 370, June, 1943.

4. OO. 400.112/13640; SPOBA 400.112/13445, 1st Ind., February, 1945.

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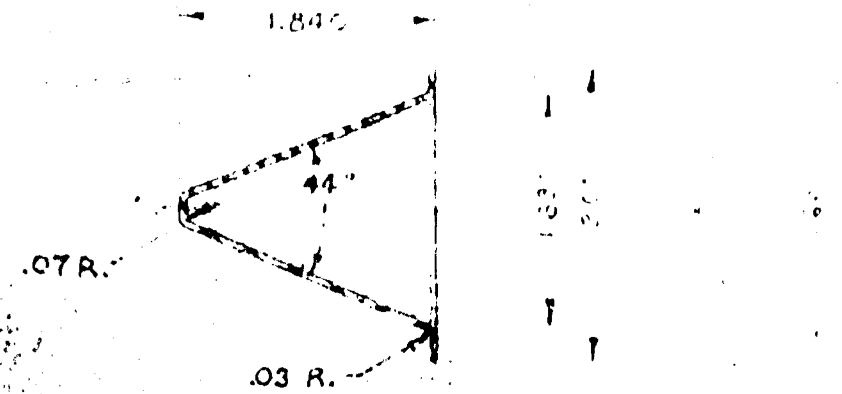
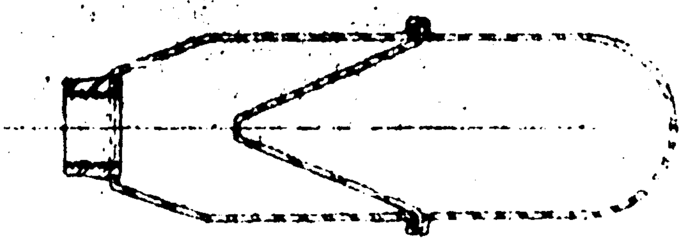


CONE

ADVISORY METAL THICKNESS .036



BODY, OGIVE AND CONE ASSEMBLY

FIGURE I

RIFLE GRENADE M9A1

CONE DIMENSIONS AND HEAD ASSEMBLY

REPRODUCED FROM
ORDNANCE DEPARTMENT DRAWING 82-1-76

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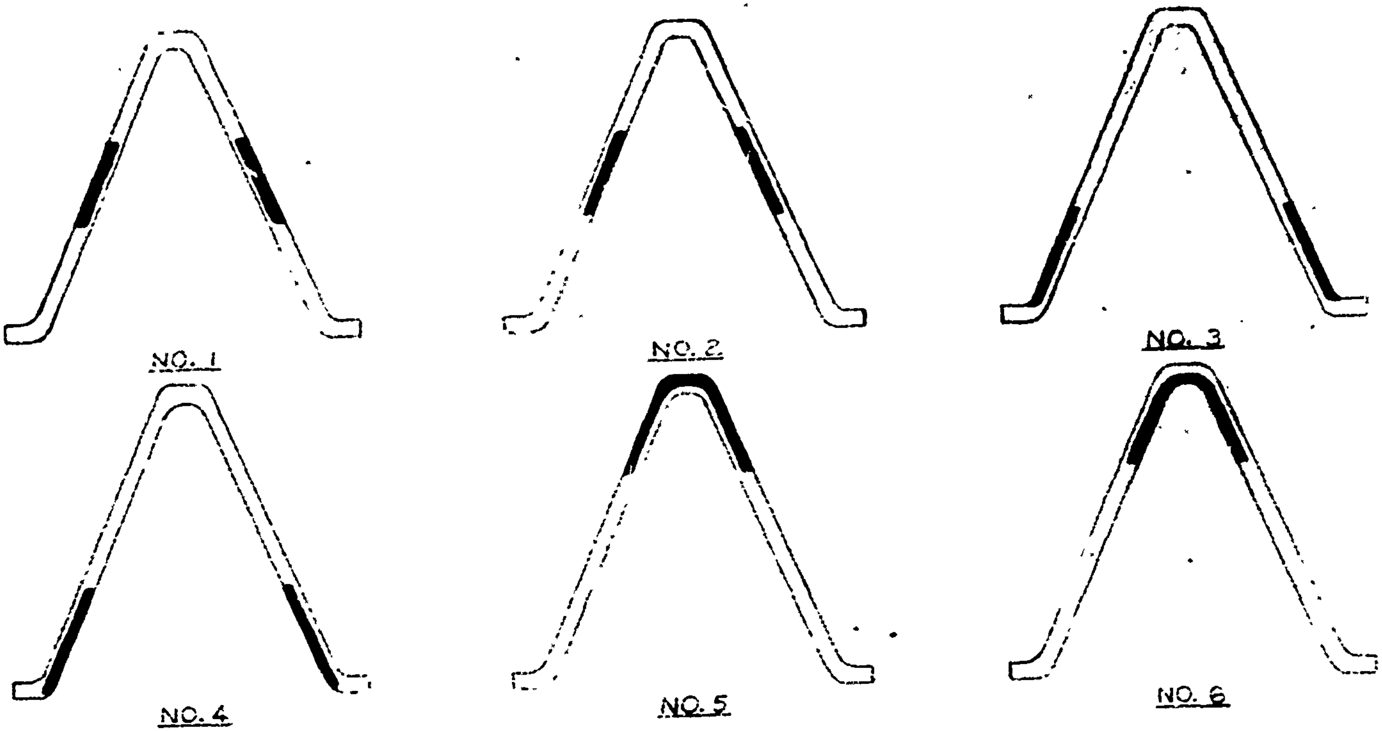

SELECTIVELY CARBURIZED REGIONS IN M9A1 CONES
(WALL THICKNESS IS NOT DRAWN TO SCALE)

FIGURE 2

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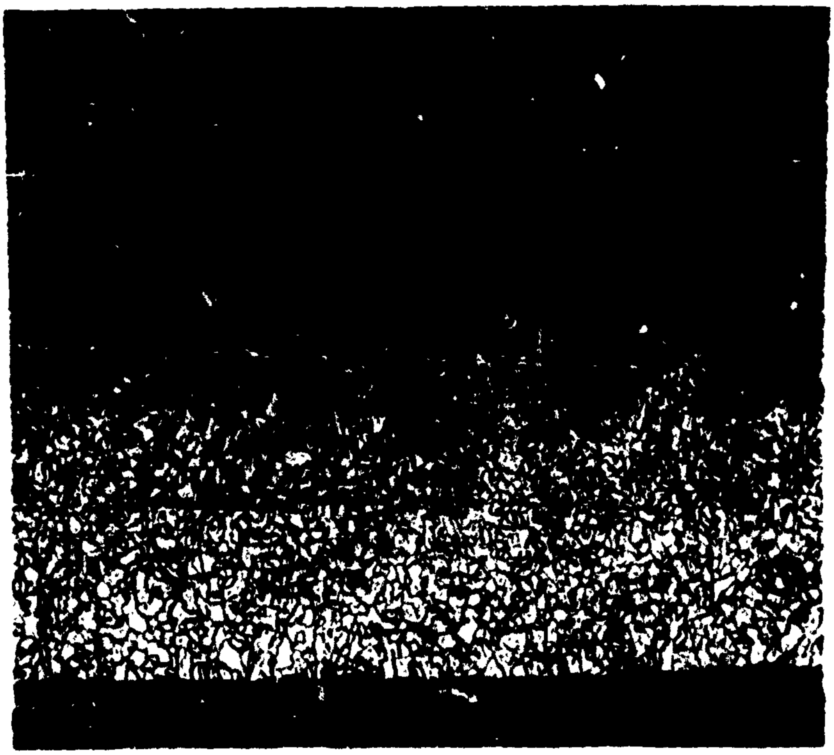

A

B

FIGURE 3

STRUCTURE OF SELECTIVELY CARBURIZED CONE BEFORE FIRING. FIGURE 3A, AT 100X, SHOWS THAT CARBON PENETRATED TO APPROXIMATELY THE CENTER OF THE WALL; COPPER ELECTROPLATE ON LOWER SURFACE INHIBITED CARBURIZATION. FIGURE 3B, AT 1000X, SHOWS STRUCTURE NEAR SURFACE CONSISTED OF PEARLITE AND FERRITE.

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Figure 4

Photomacrographs showing appearance of recovered slugs and fragments. Photographed at 1.5X; reduced slightly in reproduction.

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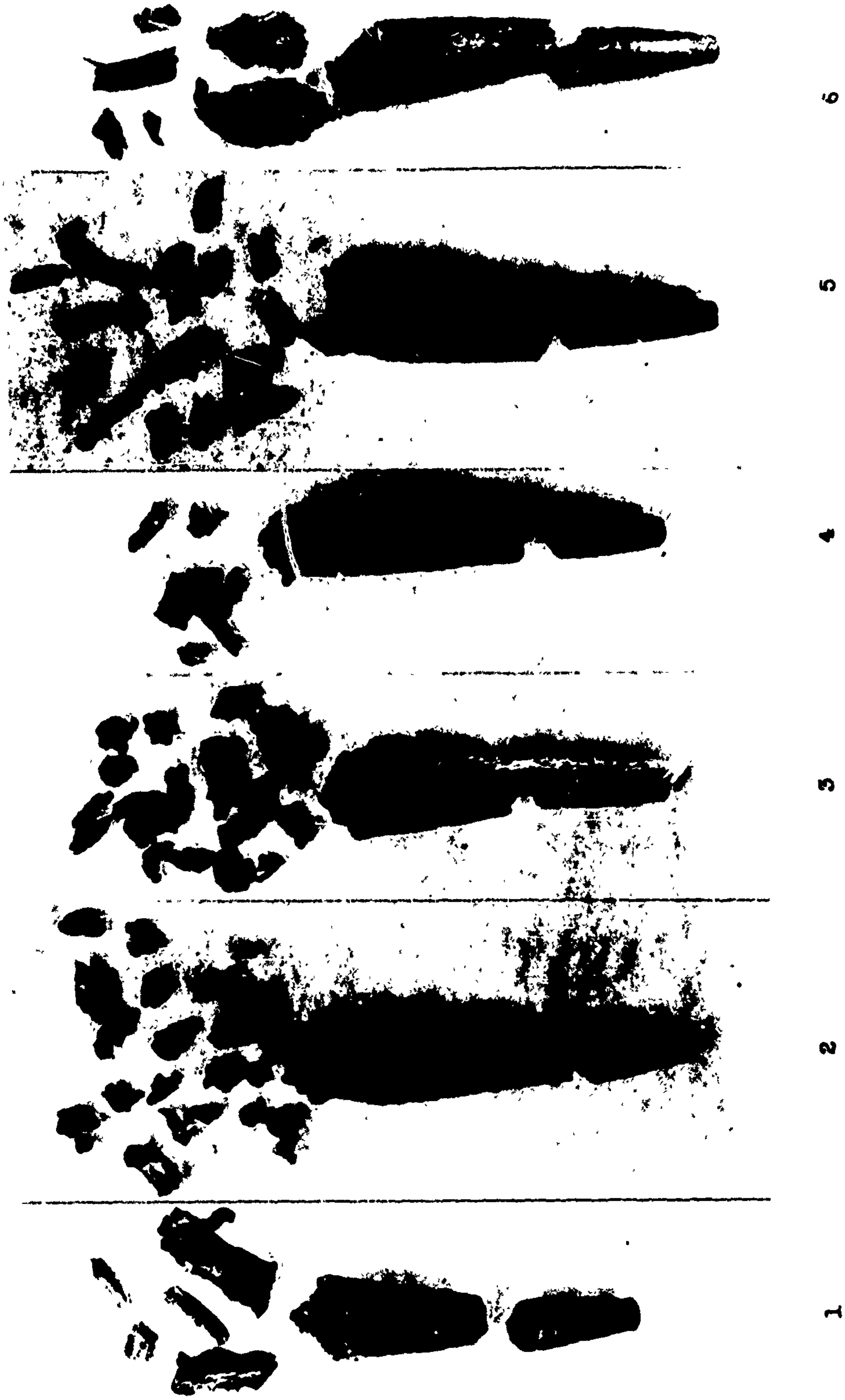

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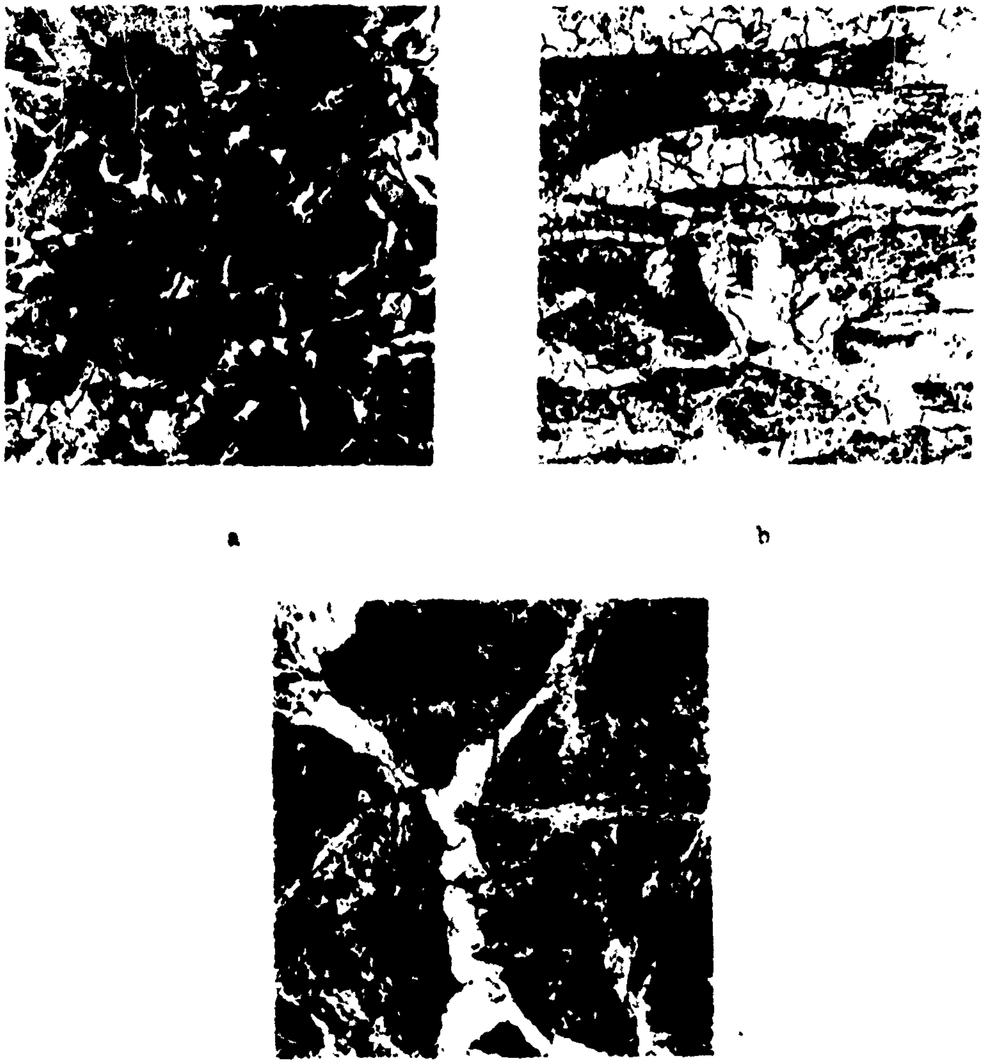
Figure 5

Photomacrographs showing structure developed on longitudinal sections through the recovered slugs by deep-etching with an acid cupric chloride reagent. Photographed at 2X; reduced slightly in reproduction.

1 2 3 4 5 6



a

b

c

Figure 6 - Structure observed in carburized areas of recovered slugs. a - Center of slug: Newly formed pearlite indicates that temperature in this zone exceeded the lower critical temperature. b - Intermediate zone: Undissolved carbides indicate that the temperature did not exceed the lower critical. c - Near surface: Some evidence of recrystallized ferrite indicates that maximum temperature in this zone was in the range 950° to 1200°F. Mag: 1000X.

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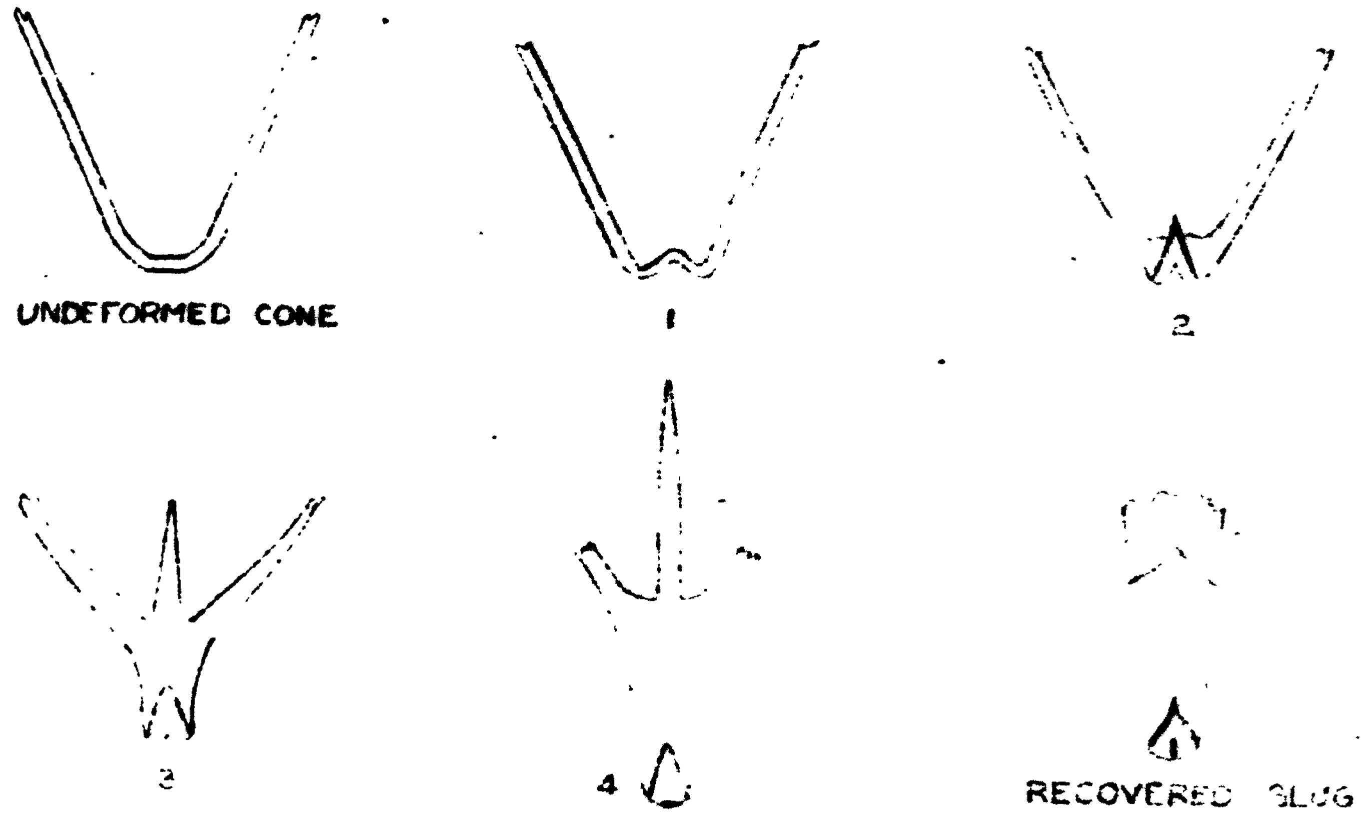

FIG. 7 SUGGESTED MECHANISM FOR COLLAPSE OF APEX REGION OF HOLLOW CHARGE CONE

APPENDIX A

Examination of Slug Formed from the Hollow Charge Liner of 7.2" Rocket*

1. This Arsenal has examined a recovered hollow charge cone from a 7.2" rocket. A summary of the results follows:

A. Chemical Analysis

The composition complied with the requirements for WD 1010 or 1015 steel. The detailed analysis is shown in Table I.

TABLE I

Chemical Composition of Recovered Cone

Element	Percentage
Carbon	0.13
Manganese	0.49
Phosphorus	0.012
Sulfur	0.021
Silicon	Not detected
Copper*	0.03
Nickel*	0.03
Chromium*	0.03
Vanadium*	0.005
Molybdenum*	0.01
Aluminum*	0.01
Tungsten*	Not detected

* Spectrographic Analysis

B. Macrographic Examination

Figure 1 shows the external appearance of the recovered slug at approximately 1.5X.

The piece was sectioned longitudinally and etched in 50% hydrochloric acid at approximately 170°F. for 10 minutes. A photomacrograph showing the resulting appearance is shown in Figure 2A. It is to be noted that there are apparently three distinct zones: (a) outer, (b) intermediate, and (c) center.

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* Reported to Office, Chief of Ordnance, OO. 400.112/13640, SPOTB-Materials Br., SPOBA 400.112/13445, 16 Feb. 1945.

In the intermediate zone there are visible a number of lines, rather regularly spaced, which point toward the forward end of the slug. There is another characteristic believed to be at least equally as important, namely, a structural pattern which is just barely visible and only in the center area, upper half of the slug in Figure 2A. Efforts were made to develop this pattern more clearly without deepening excessively the cracks and line structure. Canfield's reagent (a copper salt etch) and long exposure to picral made the structure visible but did not develop sufficient contrast for photography; the pattern was therefore sketched. A reproduction of the sketch is presented in Figure 2B.

C. Metallographic Examination

To facilitate metallographic examination, two pieces were cut at approximately one third of the length from either end of the slug and were mounted with the longitudinal plane through the center exposed for examination. The structure of the outer, intermediate, and central zones did not vary appreciably between the two locations. The photomicrographs at 100X and 1000X presented in Figure 2C were prepared at positions A, B, and C shown in Figure 3 and are representative of the structure of the outer, intermediate, and central zones, respectively. The photomicrographs are mounted with the vertical edges approximately parallel to the longitudinal axis of the slug. Several comments on the structure appear to be pertinent:

Position A - Outer zone - Structure consists of spheroidal carbides in a matrix of ferrite. There is no evidence of cold work distortion in the ferrite.

Position B - Intermediate zone - Structure consists of pearlite and some relatively large carbides in a matrix of ferrite. Apparently this zone was heated enough for a sufficient time to induce a solution of most, but not all of the carbides; subsequent cooling developed the structure indicated. The ferrite grain size is approximately the same as that of position A. In the upper micrograph at 100X there is a line running at approximately 45°. This line appears to be related to the line structure which was noted after etching with hot hydrochloric acid (figure 2A).

Position C - Central zone - The structure is similar to that of Position B. Although the ferritic grain size is somewhat irregular, it is approximately the same as that of positions A and B. There are some crack lines visible in the lower power micrograph.

D. Hardness

Due to the fact that a smaller impression is made with the Vickers Diamond Pyramid indenter than with the Rockwell ball, it was felt necessary to use Vickers readings, particularly in the outer zone near the edge, to obtain reliable values. The results of a Vickers Diamond Pyramid, 5 Kg. Load, Survey are shown in Figure 3. The hardness varied from 89 D.P.H. (equivalent to 47 Rockwell B according to A.S.T.M. Designation E-33-42) to 116 D.P.H. (equivalent to 65 Rockwell B). Although there was no clear trend, the central zone appeared to be slightly harder than the other regions.

2. Discussion of Results

Interpretation of the macrostructure and microstructure is complicated by the fact that the circumstances surrounding the deformation are unusual. In particular, the time during which the structural changes are effected is not known but presumably is very short. There is evidence that a high temperature was developed in the cone during deformation, but it is difficult to make even a rough estimation of the maximum temperature because dissolution of carbides requires diffusion of carbon and is a function of both time and temperature. Further, there is very little literature on rapid transformations, and, even if the time were known, it would still be impossible to supply a precise estimate for the maximum temperature. The ferrite grain size and other microstructural characteristics of the original cone are not known. For these reasons, and also because only one slug was examined, the following statements should be regarded only as "intelligent guesses" and not as incontrovertible conclusions.

It appears that the lineage structure developed by a hot hydrochloric acid etch (Figure 2A) represents planes of shear (See also Figure 2C, 100X micrograph for position B), whereas the pattern developed by long exposure to a picral etch represents the segregation ("fiber") pattern and is more indicative of the nature of metal flow.*

It is suggested that the outer layers undergo very little longitudinal shifting during collapse. As the metal on or near the inner surface collapses inward, meeting other metal flowing toward the center, with further pressure from the outside, a forward moving stream is generated at the center. The stresses leading to complete collapse generate shear lines which were made visible by a hot acid etch.

With respect to the temperature reached, the fact that the outer zone contains ferrite undistorted by cold work and that spheroidal carbides are present suggests that the temperature of this area was

* Although this explanation may still be correct, it is believed now that the pattern developed by long exposure to picric acid is probably a reflection of a directional texture which was present in the original cone distorted by deformation of the cone. Metal flow appears to be similar to that noted in the M9A1 cones.

above the recrystallization temperature of ferrite (approximately 1200°F.), but below the lower critical temperature (1335°F.) (The temperature might have slightly exceeded the critical for a very short time without inducing carbide solution.) The intermediate and central zones appear to have been heated over the lower critical temperature, since the spheroidal structure has been almost completely replaced by a pearlitic structure. There is no evidence of complete fusion. As indicated previously, it is not possible to make a more precise statement with respect to the maximum temperature.

It appears that a portion of the rear of the slug was not recovered. The forward end appears to have been distorted slightly by impact with the recovery medium, as indicated by the bulging and cracks in this area.

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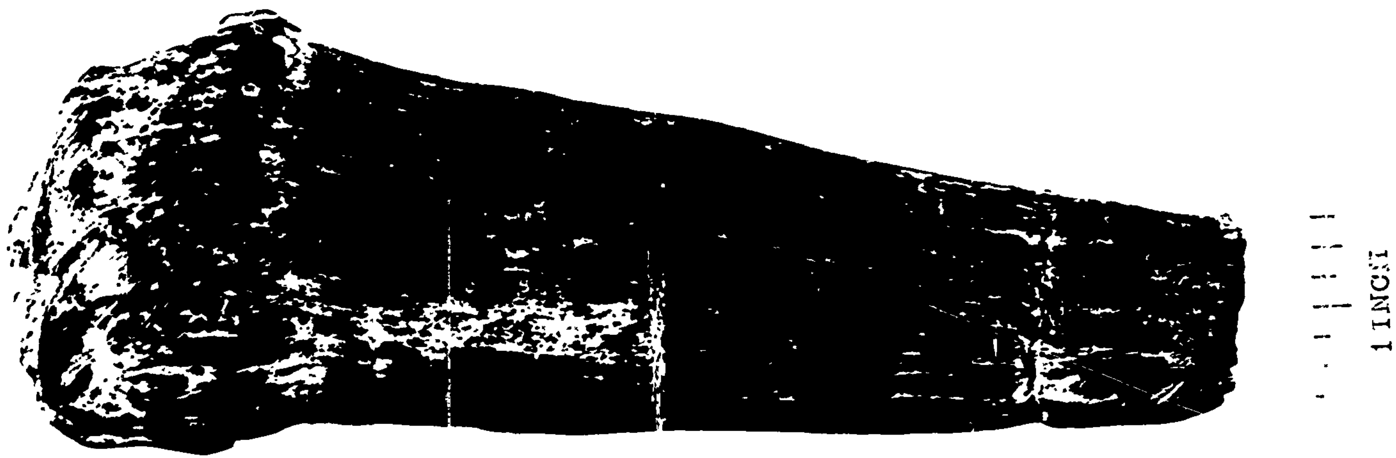

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FIG. 1

NEG. #15118-1
RECOVERED HOLLOW CHARGE CONE FROM A 7.2 INCH ROCKET. VIEW SHOWING EXTERNAL APPEARANCE.

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FIG. 2

NEG. #15118-2
PHOTOMACROGRAPH OF CROSS-SECTION OF RECOVERED HOLLOW CHARGE CONE FROM 7.2 INCH ROCKET.
APPROXIMATELY 1.5X. ETCHANT: HOT 50% HYDROCHLORIC ACID.

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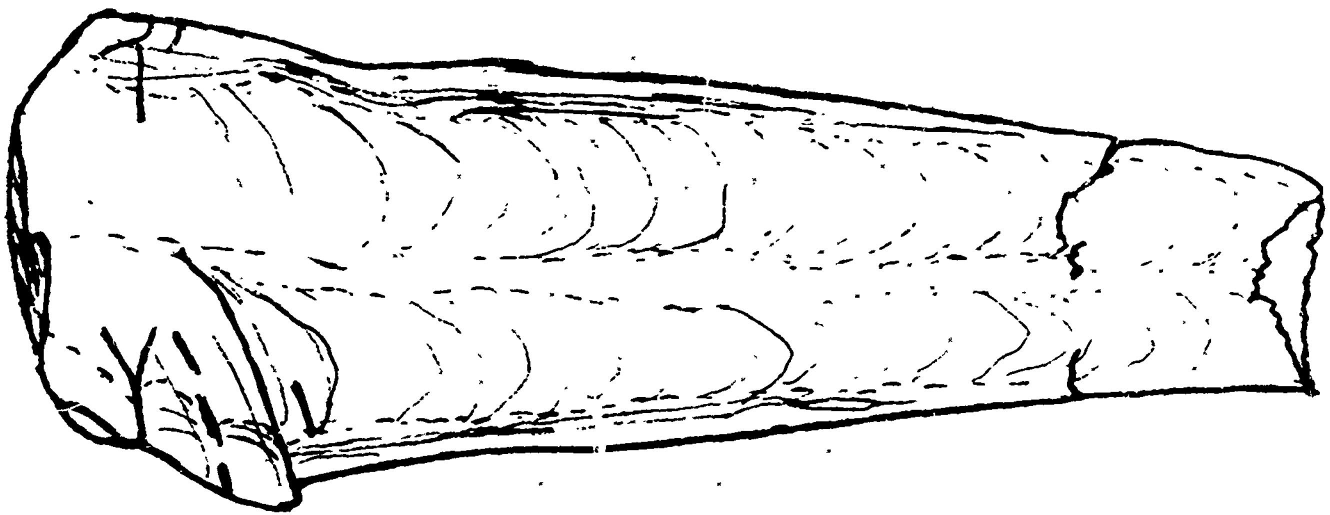

FIG. 2B

SKETCH SHOWING "FIBER PATTERN" IN SLUG FROM 7.2" ROCKET

NEG. #15160

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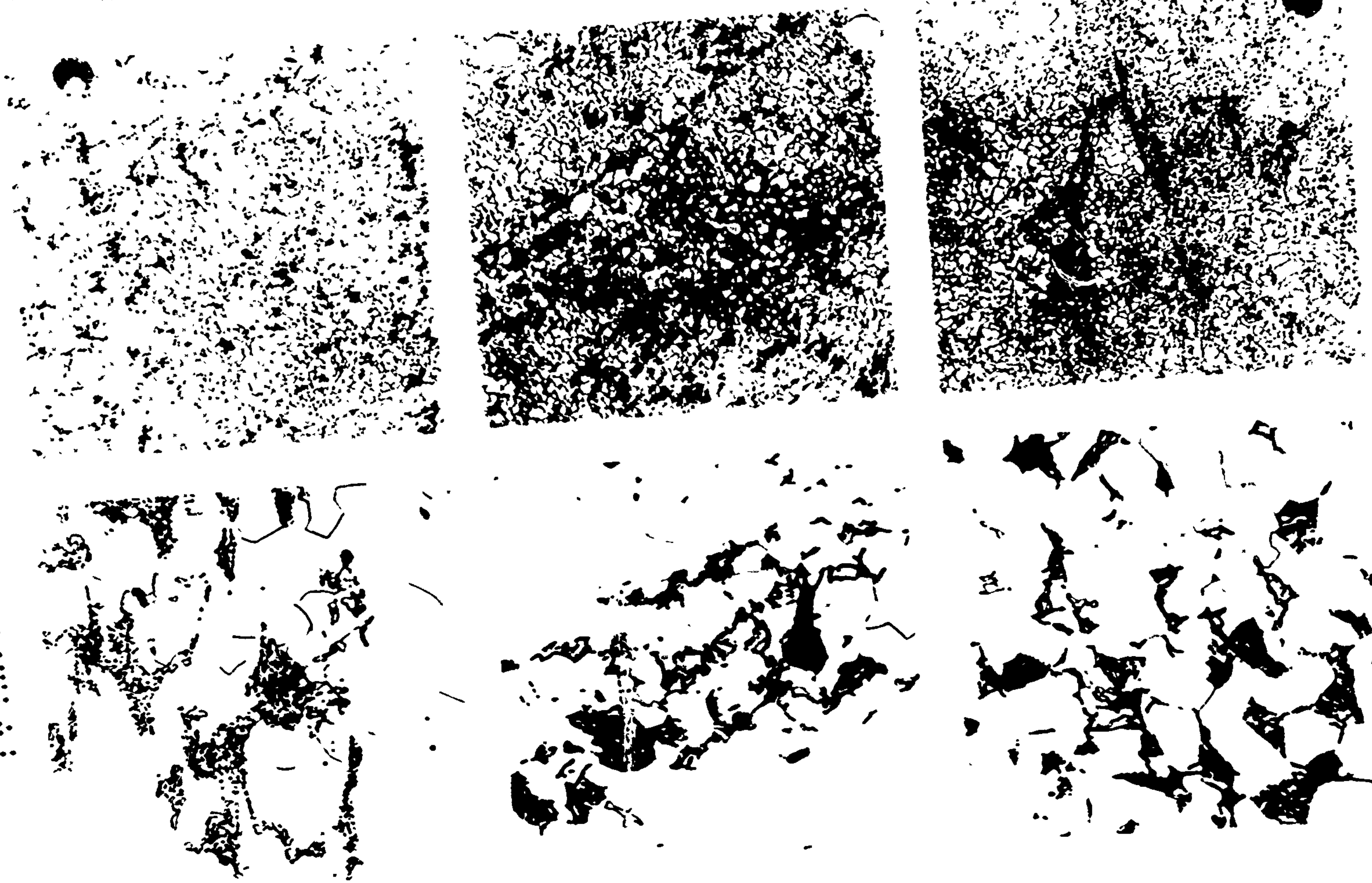

POSITION A

POSITION B

POSITION C

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NEG. #15154

FIGURE 2C - PHOTOMICROGRAPHS SHOWING STRUCTURE OF 7.2" SLUG AT POSITIONS INDICATED IN FIGURE 3. EACH MICROGRAPH IS MOUNTED WITH THE VERTICAL EDGES APPROXIMATELY PARALLEL TO THE LONGITUDINAL AXIS OF THE SLUG. UPPER MICROGRAPHS AT 100X, LOWER ROW AT 1000X.

ETCHANT: NITAL PLUS PICRAL.

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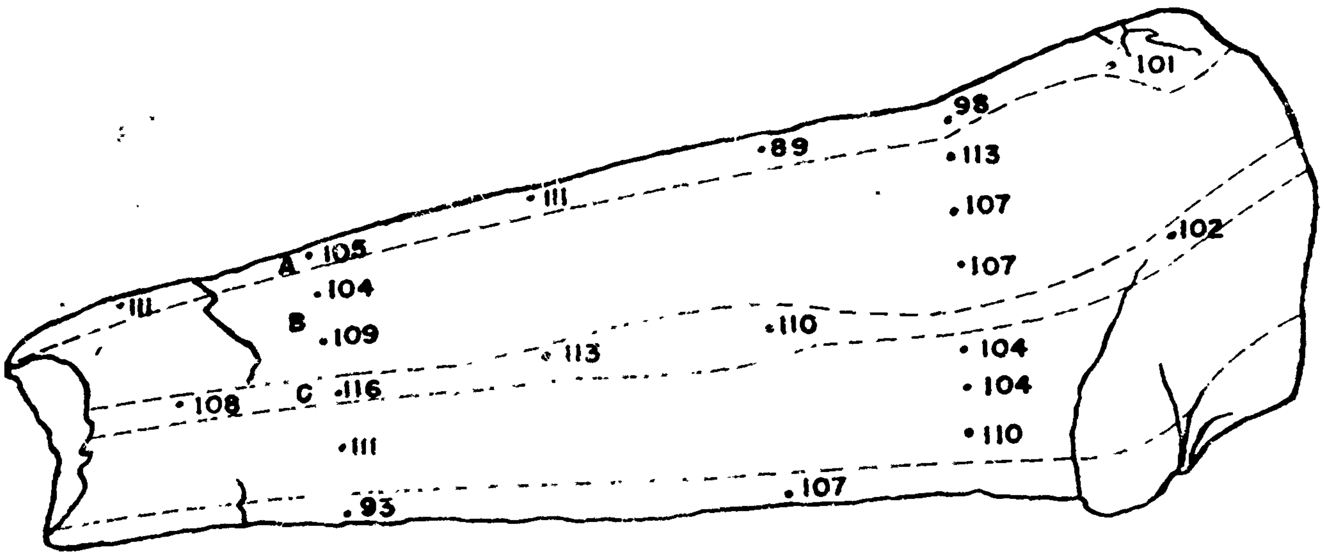

HARDNESS SURVEY ON RECOVERED HOLLOW CHARGE CONE FROM 7.2 INCH ROCKET. HARDNESS VALUES ARE DIAMOND PYRAMID (VICKERS) HARDNESS NUMBERS OBTAINED WITH 5 KG. LOAD. (LETTERS A,B,C INDICATE POSITIONS AT WHICH PHOTOMICROGRAPHS WERE PREPARED)

FIG. 3

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APPENDIX B

Comments by Dr. Birkhoff* on letter report**
Outlining Results of the Current Investigation.

1. The observed lack of shifting of longitudinal distances (not really areas) near the surface is predicted by the "jet theory" of lined hollow charges, according to which the surface consists of "free streamlines" (in the hydrodynamic sense).

2. The observed shifting forward in the slug of regions interior to the cone is also predicted by this theory, which expresses mathematically the picture described in Figure 7. This picture is just that revealed by the high-speed X-ray pictures of Major Clark and Dr. Seely.

3. The inverted V structure near the apex has not been observed before. It is probably due partly to the fact that the "cones" are actually rounded near the apex, but it should be mentioned that computations by Professor Emmons, based on the hydrodynamic approximation, indicate the existence of such a region, even with perfect cones.

4. The breaking of the slug has also been observed in X-ray pictures, but is not fully understood.

5. The heating of the central regions has been predicted on the basis of the hydrodynamic jet theory; it may easily be shown mathematically that the greatest deformation occurs there.

6. It is believed that the present tests assist in removing the mechanism of cone collapse from the realm of controversy, as they support the overwhelming evidence from X-ray pictures.

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